

# Reduced Input Throw and High-speed Driving

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**Abstract:** The U.S. Army is examining new and evolutionary concepts for military vehicles for their future force. In particular, drive-by-wire technology coupled with non-standard driving control devices have the potential to lead to improved driving performance, reduced Soldier training time, crash prevention, smaller vehicle space claims, and improved vehicle safety in military vehicles. However, several human performance issues are associated with non-standard control devices for manual driving. Specifically, this investigation focuses on the critical issue of the impact of the reduced “throw” (i.e., angular range of motion of the control device) that is typically associated with yoke and joysticks as compared to conventional steering wheel devices. Four participants were examined as they executed straight road lane-keeping and obstacle avoidance tasks. Two difference devices (yoke, steering wheel) and six linear steering ratios (32.4:1, 16.2:1, 6.5:1, 3.2:1, 2.2:1, 1.6:1) were examined. The results indicated an upper limit of 6.5:1 steering ratio for a simulated 8-wheeled military vehicle. These results provide a first step for developing non-linear or speed variable steering ratios that are appropriate for high- and low-speed driving, road surfaces, and cross country terrain.

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## Introduction

The U.S. Army is examining new and evolutionary concepts for military vehicles for their future force. In particular, drive-by-wire technology coupled with non-standard driving control devices have the potential to lead to improved driving performance, reduced training time, crash prevention, smaller vehicle space claims, and improved vehicle safety (for discussion, see Andonian, Rauch, & Bhise, 2003). However, several human performance issues are associated with non-standard control devices for manual driving. Specifically, this investigation focuses on the critical issue of the impact of the reduced “throw” (i.e., angular range of motion of the control device) that is typically associated with yoke and joysticks as compared to conventional steering wheel devices.

As drive-by-wire technologies develop, control devices with limited throw are being considered for the control of military vehicles. A consequence of the limited throw is that more direct control (lower controller position to wheel angle ratios or steering ratios) is likely to be used for military vehicles. For example, a  $\pm 60^\circ$  yoke in a typical 20-ton, 8-wheeled vehicle will result in a linear steering ratio of approximately 1.6:1. This can be compared to steering ratios in conventional automobiles that are an order of magnitude higher. Such a large reduction in steering ratio may allow subtle hand movements to provide finer control; however, the potential of inadvertent control inputs may limit the steering system effectiveness (Lee, 2000). The criticality of this issue is likely to arise in higher-speed tasks such as lane-keeping where movements of a steering wheel in a conventional vehicle are on the order of 5 to  $10^\circ$  (Lee, 2000; Andonian et al., 2003) as compared to 0.5 to  $1^\circ$  in our military vehicle exemplar.

One approach to overcoming the reduced throw devices is to implement speed variable steering systems, which have been proposed since the 1960s (Wohl, 1961). Such systems have been studied (for examples, see Olson & Thompson, 1970; Huang, Smakman, & Guldner, 2004) and made their way into some commercial automobiles. However, the extant literature has generally examined a higher range of steering ratios than applicable in the future force designs. A second approach is to implement a non-linear relationship between the controller and the wheel angle. For example, a piecewise linear function with a 3.2:1 steering ratio around the center yoke position and a 1.2:1 steering ratio on the extreme yoke positions has been implemented in the field on an 8-wheeled military vehicle testbed. For either approach, an understanding of the minimum steering ratios to accomplish the higher speed tasks for the military vehicles in question is required. This effort will define an upper range of steering ratios. Further research can then examine how to vary from this upper limit to steering ratios appropriate for lower speed maneuvers and off-road terrain types.

## Purpose

The purpose of this study was to identify a linear steering ratio that adequately enabled the relatively small operator corrections needed for higher speed non-evasive road driving maneuvers in an 8-wheeled military vehicle. As such, six steering ratios for each of two separate devices were examined for lane-keeping and lane-changing behaviors. Thus, this study is intended to provide information regarding appropriate upper limit for steering ratios; follow-on studies will utilize this information for the development of non-linear or adaptive steering ratios.

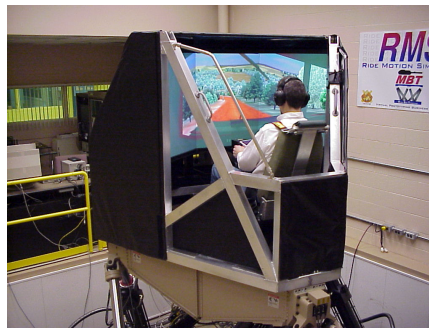
## Methods

### Participants

Four male U.S. Army Tank Automotive Research, Development, and Engineering Center (TARDEC) engineers that were free of any recent cold, flu, and anti-motion sickness medications volunteered for this experiment. All participants had a minimum of 12 hours of experience driving simulated military vehicles on a motion simulator and had  $1.4 \pm 0.7$  (means  $\pm$  standard errors are reported throughout) hours of experience driving actual military vehicles. The average age of the participants was  $33.8 \pm 5.6$  years. The voluntary, fully informed consent of the persons used in this research was obtained as required by 32 CFR 219 and AR 70-25.

### Apparatus

The present study used TARDEC's Ground Vehicle Simulation Laboratory's (GVSL) six degree-of-freedom Ride Motion Simulator (RMS; MTS Systems, Minneapolis, MN) illustrated in Figure 1. The system integrates in real-time several major components including: a motion system, a vehicle dynamics model, an audio generation system, a visual display system, a data acquisition system, a visual database, a terrain database, and a simulation framework. At GVSL these simulation subsystems have been in place for several years (Meldrum, Paul, Reid, & Zywiol, 2003; Meldrum, Paul, McDowell, & Smyth, 2004), and is outlined here.

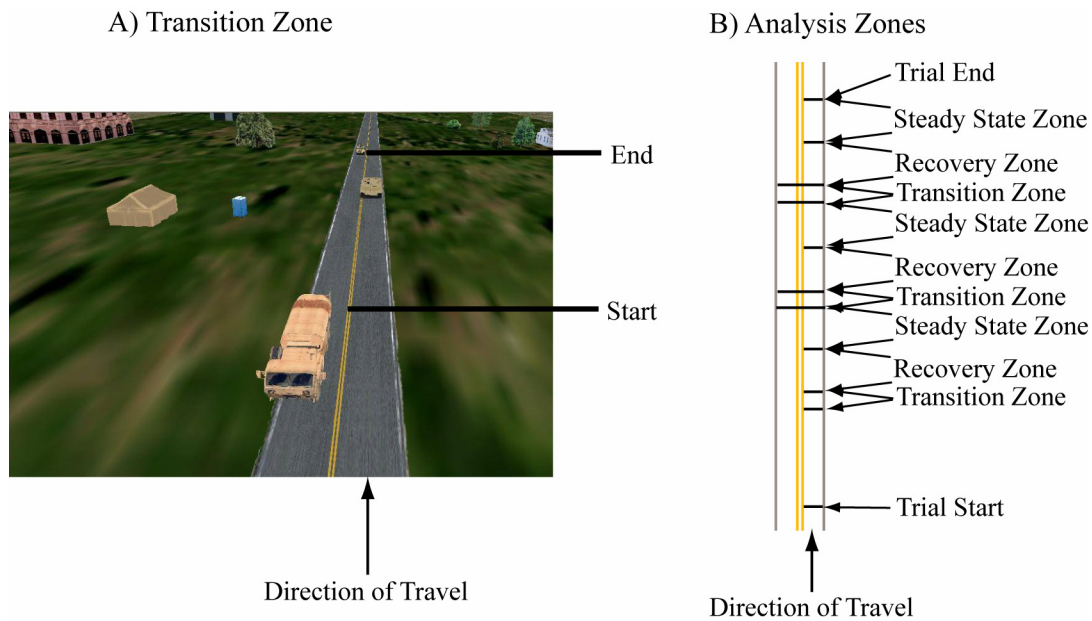


**Figure 1: Six degree of freedom Ride Motion Simulator.** The cab configuration is generally similar to that in the experiment except for the displays (see text for display sizes).

Participants operated a simulated Stryker vehicle, which is an approximately 20 ton 8-wheeled military vehicle with four wheel steer. The physical set-up for this experiment included: three flat panel 4:3 ratio, 19-inch displays each in landscape orientation and placed side-by-side and a High Mobility Multipurpose Wheeled Vehicle (HMMWV) seat. Two steering controllers were used in the experiment: a Momo Force (Logitech, Fremont, CA) mini-steering wheel, and a MSI Military Grade 5-3-G5831 Yoke (Measurement Systems Inc., Fairfield, CT). For both devices,  $\pm 60$  degrees of throw was used for this experiment.

The terrain database represented an approximately 4.0 km two-lane flat straight road. Along the road were positioned three identical sets of three stationary vehicles (9 total vehicles), set-up in a manner to force the participants into a double lane change (Figure 2A). Within each “transition zone,” the first obstacle located in the left lane was a Transport Heavy Expanded Mobility Tactical Truck (HEMTT). Positioned 56 m beyond the HEMTT and in the right lane was a French Leclerc Tank. The final vehicle was a HMMWV, which was positioned 60 m beyond the Tank and in the left lane. Other than the nine vehicles, the two lane road was clear of obstacles.

Cross-winds (relative to the direction of the road) lasting 1s were generated at random times. These winds generated forces that was sufficient to have a minor impact on the path of the vehicle and induce a corrective action.



**Figure 2: Course Design.** Participants traversed the course at a controlled 45 mph. A) An overhead view of the three stationary vehicles in the transition zone. B) The relative positions of the analysis zones over the 3.0 km course.

## Procedures

Participants were briefed on the purpose of the study, introduced to the equipment and experimental procedures, and completed a human use consent form. Participants then entered the RMS and began the 12 total conditions (two controllers by six steering ratios ranging from 32.4 to 1.6:1). For each condition, the participants drove approximately 3.0 km on a straight highway (lane-keeping task) and performed three double lane changes (lane-changing task) as illustrated in Figure 2. The initial 109 m double lane change began at approximately the 1.0 km point and each lane change was spaced 0.5 km apart. The participants were instructed to maintain the Stryker vehicle in the right lane except for during the double lane change maneuvers. In this experiment only steering could be controlled as the speed was held fixed at 45 mph. Participants repeated the 3.0 km trials until the experimenter subjectively assessed that a plateau in performance had been reached. All participants completed a minimum of three training trials (9 km of driving) per condition. Immediately after the training trials, the participants completed the experimental run for that condition. After a short break this process was then repeated for each subsequent condition within a controller type. On a second day within one week of the original experimental day, the participants returned and completed the same process for the second controller type. The conditions were blocked by controller type and the order of the steering ratios was randomized within each controller type. The presentation of the controllers was balanced across participants. Total experimental time for each participant was approximately 6 hrs.

## Data Reduction

The vehicle model states (position in the database, vehicle velocities and accelerations) and the controller inputs of the participant were collected at 60 Hz. To derive the measures of interest, first the database was divided into 9 data collection zones. Transition zones were defined as the point at which the double lane change could begin to the point at which the double lane change must be completed. Recovery zones were the 300 m after the transition zones. Steady state zones were the 300 m after the recovery zones. Three of each zone type existed for the 3.0 km course (see Figure 2B).

Within each zone several variables were examined including: weighted time-to-lane crossing/obstacle contact (wTTC), percent time out of lane/contacting obstacles (Err%), standard deviation of lane position (LP<sub>dev</sub>), mean angular acceleration (AA), standard deviation of steering input (SI<sub>dev</sub>), total power of the steering input (SI<sub>pow</sub>), and mean frequency of the steering input (SI<sub>freq</sub>).

Three driving performance measures were calculated. For the recovery and steady state zones, a lane crossing was determined if any one tire was fully outside of the lane. For the transition zones, a lane crossing/obstacle contact was determined if any one tire was fully outside of the two-lane road or if any part of the vehicle contacted one of the three stationary vehicles. Using these criteria, time-to-lane crossing/obstacle contact (TTC) was estimated using vehicle's initial position, velocity, and angular velocity for each time point and with a maximum TTC constrained to 10 s (maxt). For each of the transition zones, a weighted average (wTTC) was computed using the following formula:

$$wTTC = [\sum_{i=1}^n ((e^{(\max t - TTC_i)^w}) / e^{\max t^w})] / n$$

where  $n$  was zone length, and  $w$  was a weighting variable. The four  $w$  values examined were 0.25, 0.5, 0.75, and 1.0. Err% was computed as the time the vehicle was outside of a lane or in contact with another vehicle divided by the total time for the zone times 100. The LP<sub>dev</sub> was the standard deviation of the vehicles offset from the center of the lane.

Three measures of the operators' interaction with the controller were calculated within each zone. The SI<sub>dev</sub> was the standard deviation of the steering wheel position. To compute power and mean frequency, power spectral density was estimated via Welch's method. A 4.2 s Hamming window zero padded to 5 s was used with 50% overlap. This created 18 total windows for the recovery and steady state zone types but only 3 windows for the transition zone type. SI<sub>pow</sub> was the total power from 0 to 5 hz. SI<sub>freq</sub> was computed as follows:

$$SI_{freq} = \sum_{f=0}^5 fp_f / SI_{pow}$$

where  $f$  is frequency and  $p$  is power.

## Statistics

The experimental design examined six linear steering ratios (32.4:1, 16.2:1, 6.5:1, 3.2:1, 2.2:1, 1.6:1), three zones (transition, recovery, steady state), and their interaction. Additionally two controllers (an MSI yoke and a MOMO limited throw steering wheel) were examined for generalizability. The statistical models were represented by mixed linear models in SPSS® 15.0

(SPSS, Inc., Chicago). For each of the dependent variables, the model included steering ratio, zone, controller, and steering ratio by zone as fixed effects and participants as a random effect. For all models, the covariance structure was variance components. Post-hoc evaluations were pairwise comparisons using the least significant difference method if the model effects were significant ( $p < .05$ ).

## Results

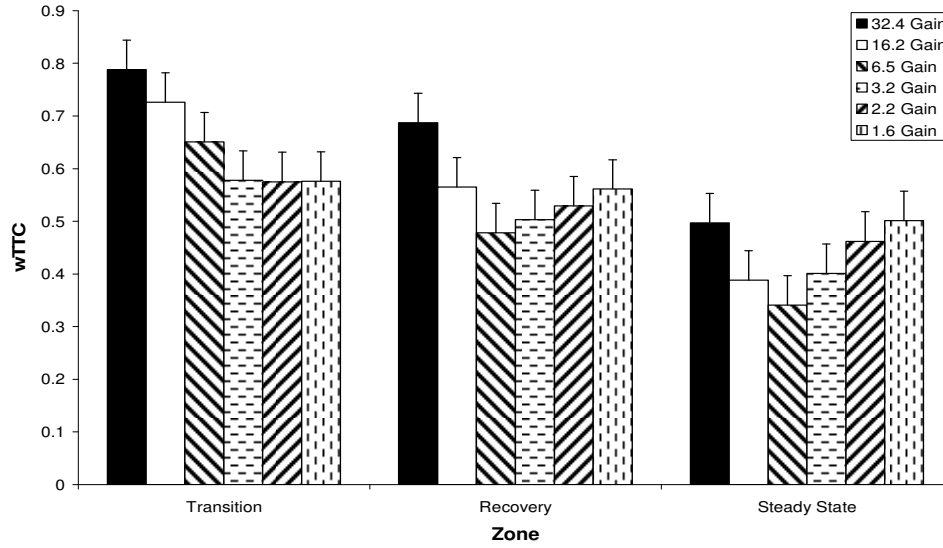
### Driving Performance

Overall, the three driving performance measures consistently indicated differences in the factors of interest. WTTC<sup>1</sup> ( $w = 0.75$ ) was observed to be significant for steering ratio ( $F(5,122) = 12.0$ ,  $p < .001$ ), zone ( $F(2,122) = 74.9$ ,  $p < .001$ ), controller ( $F(1,122) = 16.9$ ,  $p < .001$ ), and the steering ratio by zone interaction ( $F(10,122) = 3.4$ ,  $p = .001$ ). Steering ratio and zone data are depicted in Figure 3 and the results indicate that the lower steering ratios generally outperformed higher steering ratios during the transition zone (i.e., lane change maneuver); however, the 6.5 and 3.2:1 ratios were generally associated with the best wTTC measures for the recovery and steady state zones. Overall, wTTC clearly changed with zone; the steering ratio main effect was superseded by the interaction. The controller main effect revealed a small but significant improvement of the MSI yoke ( $0.52 \pm .05$ ) over the Momo wheel ( $0.58 \pm .05$ ).

The mixed model analysis of Err% also indicated main effects of steering ratio ( $F(5,122) = 17.8$ ,  $p < .001$ ), zone ( $F(2,122) = 17.0$ ,  $p < .001$ ), and steering ratio by zone ( $F(10,122) = 1.9$ ,  $p < .05$ ); however, the controller main effect was not significant ( $p > .25$ ). The relationships for steering ratio and zone effects for Err% were nearly identical to those depicted in Figure 3 and are therefore not illustrated further.

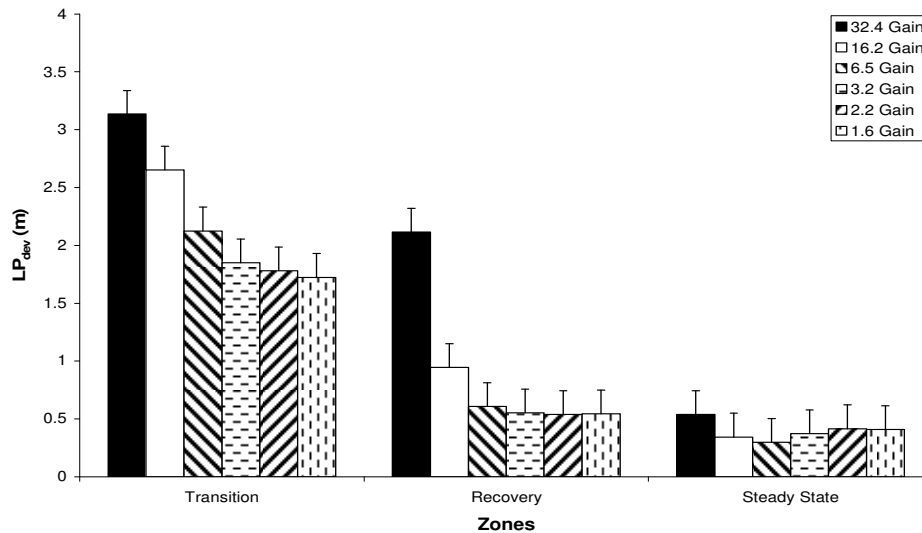
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<sup>1</sup> WTTC was examined with four  $w$  values, where the higher the  $w$  value, the stronger weighting of small TTC's on the final wTTC value. The statistical analysis was generally similar across all four  $w$  values, that is, for all four analyses significance was observed in all three main effects and the interaction (all  $F$ 's  $> 2.6$ , all  $p$ 's  $> 0.08$ ). The wTTC with  $w = 0.75$  is reported here and it reflects 50% of the weighting to TTC's under 1.5 s.



**Figure 3: Zone by steering ratio interaction for wTTC.** Lower wTTC values indicate that generally TTC was higher. That is a wTTC of 1.0 indicates that the vehicle was out of the lane for the entire zone and a wTTC less than 0.005 indicates that the TTC was greater than 10 s for the entire zone. See text for explanation of the interaction.

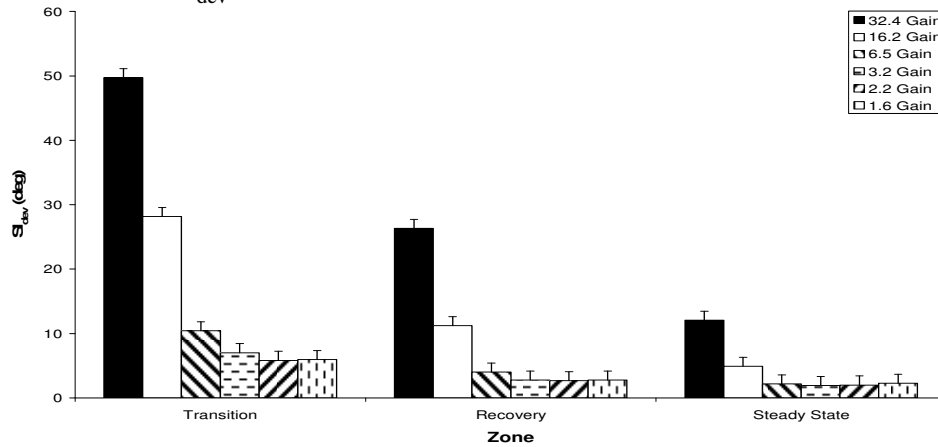
The analysis of  $LP_{dev}$  revealed significant main effects of steering ratio ( $F(5,122) = 20.5, p < .001$ ), zone ( $F(2,122) = 218.7, p < .001$ ), and the steering ratio by zone interaction ( $F(10,122) = 4.6, p < .001$ ); however, the controller main effect was not significant ( $p > .9$ ). Steering ratio and zone data are depicted in Figure 4 and the results slightly differ from those of the wTTC and Err%. The decrease in variability across zones and the decreased variability for the lower steering ratios in the transition zone are consistent with the gains indicate that the lower steering ratios wTTC and Err%. However, the improved performance for the 6.5 and 3.2:1 ratios are non-existent in the recovery zone and reduced in the steady state zone.



**Figure 4: Zone by steering ratio interaction for  $LP_{dev}$ .** See text for explanation of the interaction.

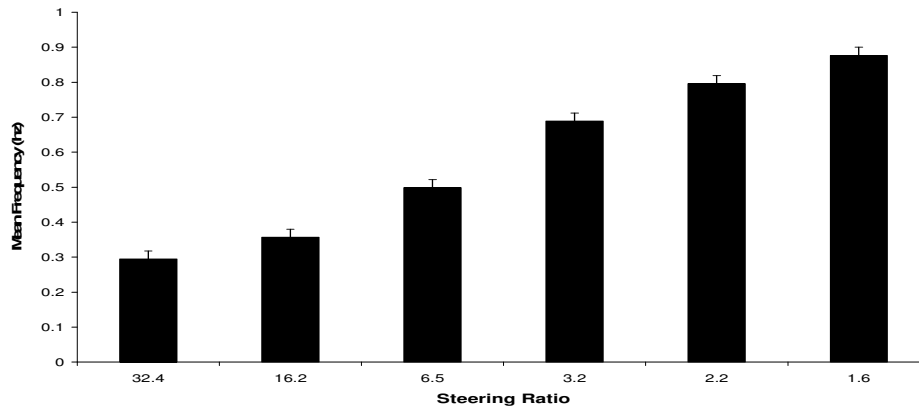
## Operator-Controller Interaction

$SI_{dev}$  was observed to be significant for steering ratio ( $F(5,122) = 240.9, p < .001$ ), zone ( $F(2,122) = 219.7, p < .001$ ), controller ( $F(1,122) = 21.0, p < .001$ ), and the steering ratio by zone interaction ( $F(10,122) = 36.9, p < .001$ ). Steering ratio and zone data are depicted in Figure 5 and the results indicate that the lower steering ratios generally outperformed higher steering ratios during all three zones; however, the relative differences were smallest for the steady state zone. The analysis also indicated more steering input variability for the Momo controller ( $11.4 \pm 0.9$  deg) than for the MSI yoke ( $8.9 \pm 0.9$  deg). The mixed model analysis of  $SI_{pow}$  also indicated significant main effects of steering ratio ( $F(5,122) = 52.8, p < .001$ ), zone ( $F(2,122) = 45.2, p < .001$ ), controller ( $F(1,122) = 7.2, p < .01$ ), and steering ratio by zone interaction ( $F(10,122) = 23.4, p < .001$ ). The relationships for these results are generally similar to that pattern found for  $SI_{dev}$  and are not illustrated.



**Figure 5: Zone by steering ratio interaction for  $SI_{dev}$ .** See text for explanation of the interaction.

The analysis of  $SI_{freq}$  revealed significant main effects of steering ratio ( $F(5,122) = 136.4, p < .001$ ), zone ( $F(2,122) = 35.2, p < .001$ ), and controller ( $F(1,122) = 17.0, p < .001$ ); however, the steering ratio by zone interaction was not significant ( $p > .7$ ). The steering ratio main effect indicating increasing mean frequency with increasing steering ratio (Figure 6). Differences were also observed between the transition zone ( $0.49 \pm 0.2$  hz) and the recovery and steady state zones ( $0.63 \pm 0.2$  hz;  $0.64 \pm 0.2$  hz respectively) and between the Momo controller ( $0.62 \pm 0.2$  hz) and the MSI yoke ( $0.55 \pm 0.2$  hz).



**Figure 6: Steering ratio main effect for  $SI_{freq}$ .** Differences between all steering ratios were observed.

## Discussion

Two limited throw controllers were implemented in a simulated military vehicle for relatively high-speed driving. Six linear steering ratios ranging from 32.4 to 1.6:1 were examined for lane-keeping and lane-changing tasks. The results indicated that driving performance and the operator-controller interactions were a function of both steering ratio and task. For the lane-changing task (transition zone), relatively direct control ratios of 3.2 to 1.6:1 enabled effective driving performance and reduced magnitude steering inputs. These findings are consistent with the notion that the rapid lane-changing maneuver requires a relatively large change in the vehicle wheel position.

For the lane-keeping task (steady state and recovery zone), the weighted time-to-contact and error percentage performance measures indicated optimal performance in the 6.5 to 3.2:1 ratio range; however, the lane position deviation and steering input deviation measures did not reveal differences in the 6.5 to 1.6:1 ratio range. The performance measures suggest an upper limit for the steering ratio of 6.5:1. This is consistent with the steering input data that indicate equal magnitude but decreasing frequencies from 6.5 to 1.6:1 ratios, which suggests fewer operator inputs at the 6.5:1 steering ratio. The differences between the wheel and yoke controllers while significant were minimal.

Importantly, for this simulated military vehicle, the 6.5:1 upper limit is less than half of the typical steering ratios used in conventional automobiles. This potentially reduces the difficulty in developing a non-linear or speed variable steering ratio that is appropriate for high- and low-speed driving, road surfaces, and cross country terrain.

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